PB81-166548

Pollution Control Practices Multimedia Environmental Goals

(U.S.) Industrial Environmental Research Lab.
Research Triangle Park, NC

Oct 80

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IERL-RTP-P-327	TECHNICAL REPORT DATA *(Please read Instructions on the reverse before completin*	
1. REPORT NO. EPA-600/J-80-224	2. Journal Article	3. R PB81-166548
4. TITLE AND SUBTITLE Pollution Control Practices: Multimedia Environmental Goals		5. REPORT DATE October 1980
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) W. D. Baasel, R. A. McAllister, and G. L. Kingsbury		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS See Block 12, below, for coauthors Baasel and McAllister; coauthor Kingsbury is with Research Triangle Institute, Research Triangle Park, NC 27709		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Journal publication; 3-5/80
		14. SPONSORING AGENCY CODE EPA/600/13
15. SUPPLEMENTARY NOTES		

16. ABSTRACT The paper reviews the development and evolution of the Multimedia Environmental Goals (MEGs) data for air, water, and land (solid waste) for discharge streams (DMEGs) and for ambient conditions (AMEGs) that are listed in the Design Institute for Physical Property Data (DIPPR) Data Compilation. The use of the MEGs for comparing the potential health and ecological damage from components, streams, and processes is presented. Cost effectiveness comparisons of alternate pollution control strategies using the MEGs are also outlined.

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Assessments	Stationary Sources	14B
Evaluation	Multimedia Environmental Goals (MEGs)	12B
Ranking		
Industrial Processes	Industrial Streams	13H
Environmental Biology		06F

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/J-80-224
Journal Article

POLLUTION CONTROL PRACTICES:

Multimedia Environmental Goals

These goals were developed to evaluate and rank a large number of pollutants for environmental assessment.

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To provide for comprehensive environmental assessments, the U.S. Environmental Protection Agency's Industrial Environmental Research Laboratory (IERL) at Research Triangle Park (RTP) is developing a procedure to facilitate quantitative evaluation and comparison of streams and processes with respect to their potential environmental impacts.

The methodology prescribes a systematic method for interpreting data obtained in environmental assessment projects. To characterize waste streams fully for environmental assessment, pollutant levels must be related to their environmental effects. The development of Multimedia Environmental Goals (MEGs) is an attempt to evaluate and rank a large number of pollutants for environmental assessment. Environmental assessment, as defined by IERL-RTP, is a study aimed at:

1. applying existing and best future definable sets of control/disposal options, to a particular set of sources, processes, or industries;
2. determining the comprehensive multimedia—air, water, and land (solid waste)—environmental loadings and environmental control costs; and
3. comparing the nature of these loadings with the MEGs, as a basis for ranking potential problems and/or control needs.

Summarized below are nine criteria important for establishing goals for environmental assessment. The MEGs methodology was developed with these considerations in mind.

1. The objective in estimating target levels is to suggest goals, not regulations.
2. In the absence of reliably documented safe levels, estimated goals levels derived from models should be conservative. Worst case assumptions should be applied in using available data.
3. Goals must not conflict with existing federal standards and guidelines.
4. For use in the environmental assessment program, it is desirable to have for each chemical a set of single value goals, which are expressed in concentration units. Two types of goals are needed for each medium (i.e., air, water, and land or solid waste); one for safeguarding effects on human health and a second to protect the ecology for the medium. Goals applicable to chemicals in discharge streams are needed and, in addition, goals for chemicals in ambient media are required.
5. Organization of the chemical MEGs should allow systematic utilization. A consistent format for each chemical is required, and consistent and convenient units should be used.
6. The overall format for presentation of goals should allow direct comparison of existing and projected "best available technology" controlled emission levels with emission goals having environmental significance.
7. A method should be devised for classifying pollutants to get comprehensive coverage without having to consider millions of compounds individually. A procedure is needed to estimate relative toxicity of classes of compounds as well as individual compounds to allow a "most-toxic-first" ordering.
8. A uniform approach in applying existing health and ecological effects data is needed as well as a means for directly delineating health/ecological effects data gaps. A wide variety of potential adverse effects including oncogenic and teratogenic effects must be considered in establishing the goals.
9. Sufficient information should be supplied with the numerical goals to allow the user to discern the extent of the data available and the basis for each goal.

Development of MEGs

Multimedia Environmental Goals describe maximum levels of chemical contaminants in ambient air, water, or land, or contained in emissions or effluents conveyed to the surrounding media that will not produce known negative effects in exposed human populations or ecosystems. In the future, an alternative set of MEGs will be developed to describe control limits achievable through technology. For the present, however, emphasis is focused on ambient MEGs and discharge MEGs based on potential effects.

Ambient MEGs (AMEGs) describe maximum acceptable concentrations of various chemicals in ambient media, based on potential ecological effects or on predicted toxic levels for humans. The AMEG concentration for any given chemical is believed to be safe for continuous exposure over a lifetime. Existing or proposed federal ambient standards or guidelines serve as AMEGs for regulated (or soon to be regulated) chemicals. Values for chemicals not addressed by federal guidelines are derived from models that utilize

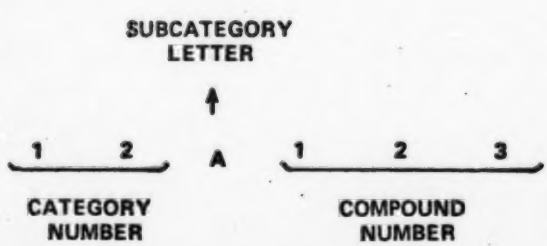


Figure 1. MEG identification numbers.

0360-7275/80/3994-0037 $01.00 1980 AIChE

CEP (Chemical Engineering Progress), 76:10, 10/80,pp 37-51.

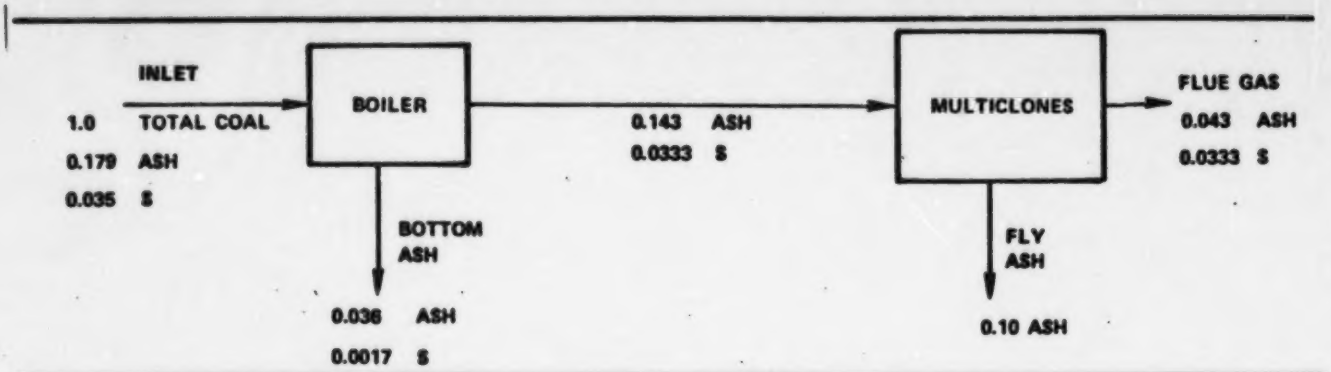


Figure 2. Material balance for base case.

available toxic effects information including potential oncogenic and teratogenic properties. Discharge MEGs (DMEGs) describe maximum concentrations believed to be safe for short-term direct exposure to a discharge stream; i.e., acute exposure effects are thought to be minimal. DMEG values like AMEGs are predicted on the basis of available data pertinent to human health effects or ecological effects. Since both DMEGs and AMEGs have been conservatively estimated, erring on the side of safety, it may not be reasonable to expect to see immediately visible health or ecological effects at concentration levels equal to or slightly higher than these values.

Chemical pollutants addressed by MEGs are organized into categories on the basis of their chemical structure. Compounds with similar functional groups are in the same category. This categorical approach allows the user to consider MEGs for a group of related compounds or for a single specific chemical. This approach is also useful in the absence of data to characterize a specific chemical of interest. For chemicals in some categories, it is reasonable to use data for a different compound of similar structure as a surrogate basis for computing the MEG values. Twenty-six major organic categories have been established for grouping the organic chemicals. Within each category, two or more subcategories are specified. A listing of organic categories and subcategories is provided in Appendix A. Inorganic categories are established for each element of interest and are organized by periodic groups.

A methodology to establish MEGs for chemical pollutants was introduced in November, 1977 (*1*). Volume I of the report described a system for generating quantitative goals for chemical substances from information currently available in the literature and proposed a list of some 600 chemicals, mostly associated with fossil fuels processes, for which goals were needed. DMEG values, formerly called Minimum Acute Toxicity Effluents (MATEs), were tabulated for many of the 600. Volume II contained background information summaries and charts displaying MEG values for 216 chemical substances from the Volume I Master List. AMEGs were formerly called Estimated Permissible Concentrations (EPCs).

In August, 1979, Volumes III and IV (*2*) were made available to supplement the 1977 MEG reports. In these volumes the original MEGs methodology is applied to 586 organic chemicals. Additional information on organics is available in the supplement to Volume I (*3*).

The concept of the MEGs has proved to be very valuable in environmental assessment, and evolution of the methodology is expected to continue. Background information for approximately 1,000 chemicals is being stored on the UNIVAC computer at IERL, Research Triangle Park, N.C. The computerized EPA data base is called MEGDAT, and will be continually updated as new information becomes available for the various chemicals and as new environmental standards are promulgated.

It is expected that new compounds and classes of compounds and their corresponding MEGs data will be added to MEGDAT as needed by the EPA, and possibly others. Presently the responsibility for MEGs development is being shifted from IERL-RTP to EPA's Environmental Criteria and Assessment Office (ECAO) at Research Triangle Park, N.C. The ECAO will eventually assume the ongoing responsibility for reviewing the MEGs data as well as the models used for calculation of the goals. The current MEGs methodology is undergoing review and refinement. New models may be added for generating MEGs, and present models may be modified.

The MEGs are a useful tool for establishing priorities among chemicals with respect to their potential environmental significance, but they should be applied with caution. The user should be fully aware of their limitations. It should be emphasized that MEGs are not to be interpreted as standards or regulations. They carry no legal authority. The values are generated to allow the approximate ranking of chemicals, according to their potential environmental effects. The goals are frequently based on data of undetermined reliability. Also the models used to calculate MEGs contain many assumptions and arbitrary safety factors. The level of confidence to be associated with any specific MEG value is not known. Potential synergistic or antagonistic effects are not accounted for in complex mixtures. The user should make any evaluation in light of the supporting data provided and the indicated basis for the quantitative value. MEGs are to be utilized, not as absolute indications of potential health or ecological impacts, but as target values which can be used to establish indices (discharge severity, etc.). These indices in turn can be useful to point out pollutants which should be studied further and discharges which should be considered for control.

There follows a description of the data selected from the MEGs reports and from MEGDAT that are to be included in the American Institute of Chemical Engineers' DIPPR Data Compilation. Also presented is some of the information comprising a chapter on MEGs to be incorporated into the DIPPR Manual for Predicting Chemical Process Design Data. Formulas are given for calculating the various MEGs. Examples of the use of the MEGs are also given below. Values in the DIPPR Data Compilation and the MEGs equations given in the DIPPR Manual for Predicting Chemical Process Design Data are expected to be updated at least annually in order to reflect changes.

DIPPR data compilation

MEGs data to be contained in the DIPPR Data Compilation include MEG identification numbers, current federal guidelines or recognition status, and AMEG and DMEG values. This information will provide a basis for characterizing the environmental significance of each chemical.

MEG identification numbers are assigned to identify uniquely each MEG compound. Compounds that are structurally similar will in general have similar identification numbers. The method for assignment of the identification numbers is illustrated in Figure 1.

The first two ciphers of the ID number indicate the MEGs category number. The third cipher indicates the subcategory to which the compound belongs. The last three digits of the ID number the position relative to other compounds within a subcategory. Compounds contained in each subcategory are numbered in order of increasing complexity.

Federal guidelines. There are numerous types of federal environmental regulations, standards, and criteria applicable to specific chemicals. In addition, certain organizations have assigned special designations to chemicals because of their potential impact on human health or on the environment.

The following types of information on regulatory actions, standards, criteria, recognition, and candidate status for specific regulation for compounds, where applicable, will be included in the MEG data provided in the DIPPR Data Compilation:

National Ambient Air Quality Standards (Primary and Secondary)
National Emission Standards for Hazardous Air Pollutants
New Stationary Source Performance Standards
Prevention of Significant Deterioration, *de minimis* levels
ACGIH Recommendation for Occupational Exposure (TLVs)
NIOSH Recommendations for Occupational Exposure
OSHA Standards
ANSI Standards
Primary Drinking Water Regulations
Secondary Drinking Water Regulations
Toxic Pollutant Effluent Limitations
EPA Consent Decree List (Priority Pollutants)
EPA Water Quality Criteria (Proposed)
EPA 1976 Water Quality Criteria
NAS/NAE Water Quality Criteria 1972
Hazardous Substance Designation
Ocean Dumping Permit Applications, Criteria
National Cancer Institute List (Chemicals Carcinogenic to Man)
Interagency Regulatory Liaison Group (IRLG), Priority List
Chemical Industry Institute of Toxicology (CIIT), Priority List
FDA Regulations
Hazardous Waste Regulations
Regulation Under Toxic Substance Control Act

Quantitative goals. AMEG and DMEG values for air, water, and soil will be provided for each chemical in the DIPPR Data Compilation, if there is available information from which to derive the MEGs. A simple-to-interpret subscript code is included to indicate the medium, the population affected, and basis for each value. Table 1, MEGs for ethylbenzene, illustrates the format planned for providing the quantitative MEG values in the DIPPR Data Compilation.

MEG values may be calculated from several different types of toxicity data such as, acute lethal dose in rates, levels associated with significant incidence of tumors, concentrations causing tainting of fish, and lethal concentrations to fish. For any given chemical, there may be available only one of the possible data types or there may be several. Thus, multiple MEG values may be listed. A coding system for MEG values has been devised to identify: 1) the medium (air, water, or land) for which the value applies; 2) the effect to be avoided (e.g., human health effects, carcinogenic effects, or ecological effects); and 3) the basis for derivation of the MEG. The coding system is outlined in detail in Appendices B and C.

Since multiple MEG values may be listed, the preferred value of each type is indicated by an asterisk in the output from the DIPPR Data Compilation, Table 1. This will allow the user to determine easily the best set of MEG values; i.e., the preferred or the lowest MEG value applicable to a given chemical in a particular medium. These are the values to be used in environmental assessment. Values other than the preferred ones are provided to indicate the extent of the available data for a given chemical or to permit selection of a particular type of toxicity data to be considered for special purposes.

As shown in Table 1, references are provided to indicate the source of the data from which each MEG value was calculated. These references will enable the user to extract additional information from the literature. The MEGs reports (*1*, *2*) provide additional supporting information and references. A compound can easily be found in the MEG reports from the six-digit MEG ID Number.

The equations currently used to generate MEG values are listed in Appendix C.

Use of MEGs

The use of the MEGs has been confined to the assumption of a linear dose-response curve. This means that if a person or the environment comes in contact with twice the amount of a harmful substance, the potential damage will be twice as great.

The DMEGs are normalizing factors with respect to health or ecological harm for contaminants in discharge streams. By dividing the discharge concentration of a stream component, dc_i, by its corresponding DMEG, a normalized dimensionless number is obtained which is called the Discharge Severity, DS_i, for substance *i*.

Table 1. MEGs for ethylbenzene.

Ambient Level Goals

Subscript Code‡	AMEG	Units	Preferred	Reference†
AH1.1	1.04E 03§	μg/m³	*	(42)
AH2.1	3.84E 02	μg/m³		(48)
WH1.1	6.00E 03	μg/L	*	(42)
WH2.1	1.40E 03	μg/L		(48)
WH3.1	1.56E 04	μg/L		(42)
WE2.1	5.00E 02	μg/L		(43)
WE2.2	2.50E 02	μg/L	*	(49)
LH3.1	1.20E 03	μg/g	*	(42)
LE3.1	5.00E 01	μg/g	*	(49)

Emission Level Goals

Subscript Code	DMEG	Units	Preferred	Reference†
AH1.1	4.35E 05	μg/m³	*	(42)
AH2.1	1.58E 05	μg/m³		(48)
AH2.2	4.35E 04	μg/m³		(49)
WH3.1	6.50E 06	μg/L	*	(42)
WE2.1	1.00E 03	μg/L	*	(43)
LH3.1	1.30E 06	μg/g	*	(42)
LE3.1	2.00E 02	μg/g	*	(43)

§1.04E 03 means 1.04×10^3.
†These fictitious numbers refer to DIPPR reference numbers in the output from the DIPPR Data Compilation.
‡Subscript code interpretations are given in Appendices B and C.

Table 2. Base case, untreated flue gas.

MEG ID No.	Compounds	dc_i, (μg/m³)	$DMEG_i$, (μg/m³)	DS_i	mr, (kg/h)	WDS_i, (kg/h)
	Flue Gas				2.255E 06	
	N_2	1.04E 09	NA			
	O_2	1.2 E 07	NA			
42B120	CO_2	3.3 E 08	9.0E 06	3.67E 01		8.28E 07
53B120	SO_2	6.3 E 06	1.3E 04	4.85E 02		1.09E 09
42B100	CO	4.0 E 04	4.0E 04	1.00E 00		2.26E 06
47B170	NO_2	6.4 E 05	9.0E 03	7.11E 01		1.60E 08
01A000	Hydrocarbon	1.0 E 04	—	—		
	Ash					
320000	Be	6.0 E 01	2.0E 00	3.0 E 01		6.77E 07
830000	Hg	6.3 E 00	5.0E 01	1.3 E-01		2.93E 05
340000	Ca	7.14E 04	1.6E 04	4.46E 00		9.92E 06
330000	Mg	7.2 E 02	6.0E 03	1.2 E-01		2.71E 05
500000	Sb	8.4 E 02	5.0E 02	1.68E 00		3.79E 06
490000	As	3.18E 02	2.0E 00	1.59E 02		3.59E 08
370000	B	1.14E 02	3.1E 03	3.7 E-02		8.34E 04
820000	Cd	2.64E 02	1.0E 01	2.64E 01		5.95E 07
680000	Cr	3.96E 03	1.0E 00	3.96E 03		8.93E 09
740000	Co	2.04E 03	5.0E 01	4.08E 01		9.20E 07
780000	Cu	5.82E 02	2.0E 02	2.91E 00		6.56E 06
720000	Fe	2.46E 05	1.0E 03	2.46E 02		5.55E 08
460000	Pb	7.8 E 02	1.5E 02	5.2 E 00		1.17E 07
710000	Mn	9.0 E 02	5.0E 03	1.8 E-01		4.06E 05
690000	Mo	5.82E 03	5.0E 03	1.16E 00		2.62E 06
760000	Ni	1.86E 03	1.5E 01	1.24E 02		2.80E 08
650000	V	1.68E 03	5.0E 02	3.36E 00		7.58E 06
810000	Zn	1.2 E 03	4.0E 03	3.0 E-01		6.77E 05
540000	Se	1.38E 03	2.0E 02	6.9 E 00		1.56E 07
350000	Sr	6.3 E 03	3.1E 03	2.03E 00		4.58E 06
380000	Al	2.75E 05	5.2E 03	5.28E 01		1.19E 08
630000	Zr	9.0 E 02	5.0E 03	1.8 E -01		4.06E 05

Ash Discharge Severity = 4.67E 03

Total Discharge Severity (TDS) = 5.26E 03

Total Weighted Discharge Severity (TWDS) = TDS × mr = 1.19E 10

$$DS_i = dc_i/DMEG_i \quad (1)$$

The higher the value of the discharge severity, the more potential damage can be expected from the compound. Because of the definition of $DMEG_i$, those compounds having discharge severities greater than unity pose possible adverse impacts for human health effects and/or ecological effects. Concentrations of chemicals with discharge severities greater than unity must be reduced, if the potential harm of a stream is to be decreased. By summing the discharge severities for all components of a stream, the Total Discharge Severity (TDS) of the stream is obtained:

$$TDS = \sum_i DS_i \quad (2)$$

Separate TDS values are obtained for human health and for ecology. The actual TDS values have meaning only in a relative sense. Each TDS is a measure of the potential damage that may be caused by a stream or an effluent. TDS values assume that the damage caused by the individual substances is additive. Synergistic and antagonistic effects are assumed to be absent.

The average composition of a flue gas leaving a coal-fired utility boiler is given in Table 2 along with the DMEGs for health. The Discharge Severities are given in the fifth column. The sum of the individual discharge severities is the Total Discharge Severity of the gas stream. In this case, since everything emitted is in the gas stream, the DMEGs used are those for a gas even though the particulate emitted is a solid which is merely entrained in a gas. For the particulates which are removed in an electrostatic precipitator and discharged as a solid, DMEGs for solid media would be used. If the particulate had been entrained in a liquid stream (as in the discharge of water from a waste treatment plant), the water DMEGs would have been used.

There are no DMEGs for nitrogen and oxygen. The value for organics has also been omitted. This is because for the example given there was not adequate analytical information to identify the individual or even classes of compounds present. If the compounds were all aliphatic hydrocarbons then to be on the conservative side, the DMEG of the hydrocarbon mixture could be assumed to be the lowest DMEG in that category.

For hydrocarbons, MEG Category 01, it would be the DMEG for cyclopentadienes, 2.0×10^5 μg/m³, then the discharge severity for the hydrocarbons would be DS = $(1.0 \times 10^4)/(2.0 \times 10^5) = 0.05$. This is a very low value compared to many of the other discharge severities in the flue gas. If, however, the hydrocarbons were mainly fused polycyclic hydrocarbons, MEG Category 21, then the lowest DMEG would be 2.0×10^{-3} μg/m³ for benzo(a)pyrene and the worst-case discharge severity would be DS = $(1.0 \times 10^4)/(2.0 \times 10^{-3}) = 5 \times 10^5$. In this case, the hydrocarbon fraction would represent the most dangerous fraction in the gas. Since in this case there is not adequate information, the hydrocarbon DMEG and DS are left blank. This means the reported TDS in this example is only a partial TDS.

Thorough analyses required

Incomplete analyses must be considered an inherent weakness in this assessment system. This often occurs because the cost of a complete analysis for each compound in each effluent is prohibitive. Frequently, the analytical techniques do not adequately describe the substances present. The more complete the analysis of a stream, the more faith one can place in the environmental assessment methodology illustrated here. There are also other instances in which there are inadequate data to determine a DMEG for a compound. Even so, the use of the approach will still more adequately describe the potential hazard that may be present than any other procedure with which the authors are familiar. If a large enough sample is available, one or more bioassay tests may be run and, from the results, a pseudo-DMEG for the system may be determined using the formulas given in Appendix C.

Discharge severities, DS_i, for ecology have not been calculated because the DMEGs for ecology of the components of airborne emissions are in many cases unavailable at this time. When enough research has been done to provide values, the same procedure just presented would be repeated using DMEGs for ecology.

From Table 2 chromium can be seen to be the potentially most dangerous substance leaving in the flue gas since it has the largest value for DS. This is potentially about eight times as hazardous as the second most dangerous compound, sulfur dioxide. This of course assumes that the components do not change in concentration or react between their release and reaching their final receptor.

If the fate of the effluent components and their ambient concentration levels were known, AMEGs could be used. Ambient concentrations of various pollutants may be measured, or the ambient concentrations may be calculated from the effluent discharge concentrations if transport models are known and if all chemical changes of the components discharged are known. The same procedure just carried out for discharge severities, DS and TDS, should then be repeated but with the use of AMEGs. In this case, an Ambient Severity and a Total Ambient Severity would be calculated.

$$AS_i = ac_i/AMEG_i \qquad (3)$$

$$TAS = \sum_i AS_i \qquad (4)$$

Separate Total Ambient Severities may be obtained for health and for ecology; i.e., AS_i for health and AS_i for ecology are not additive.

The total discharge severity is an excellent means for determining whether a given stream is potentially more dangerous than an equivalent mass or volume of another stream. However, it does not take into account the total mass of the outputs. Considering only TDS, one cannot distinguish between two streams which have the same total discharge severity but differing flow rates.

For example, if two streams have the same Total Discharge Severities, one would think that the environmental impacts would be similar. If, however, the first stream had a mass flow rate of 1,000 kg/yr, while the second had a flow rate of 1,000 kg/h, the potential total environmental impact of the streams would be quite different. The second stream has several thousand times the yearly impact of the first. To account properly for the discharge stream flow rate, the Total Weighted Discharge Severity (TWDS) was conceived. The TWDS is the mass flow rate of the entire discharge stream multiplied by the Total Discharge Severity, and thus carries dimensions of mass per unit time; e.g., kg/h.

$$TWDS = \sum_i WDS_i = TDS \times mr \qquad (5)$$

Weighted Discharge Severities for individual components, WDS_i, may also be computed as:

$$WDS_i = DS_i \times mr \qquad (6)$$

To compare processes and streams having different flow rates, the Total Weighted Discharge Severity should be used. Values for TWDS may be calculated for each stream and are intended to indicate the total impact on the environment per unit time.

TWDS for comparison

Because of the effect of flow rate just discussed, the Discharge Severity or Total Discharge Severity of an entire process having more than one exiting stream cannot properly be determined. Total Discharge Severities of streams having different flow rates should not be summed. Rather, if one wants to compare the impact of a process having several streams, compute the TWDS for each stream and sum them.

There is no equivalent to a Total Weighted Discharge Severity for ambient conditions. This is because the harm caused by a substance to a receptor is a function of its concentration. Hence, if the concentration is known at the point of contact, that should be sufficient to determine the potential harm. However, the ambient concentration at a given point relative to the discharge point is a function of

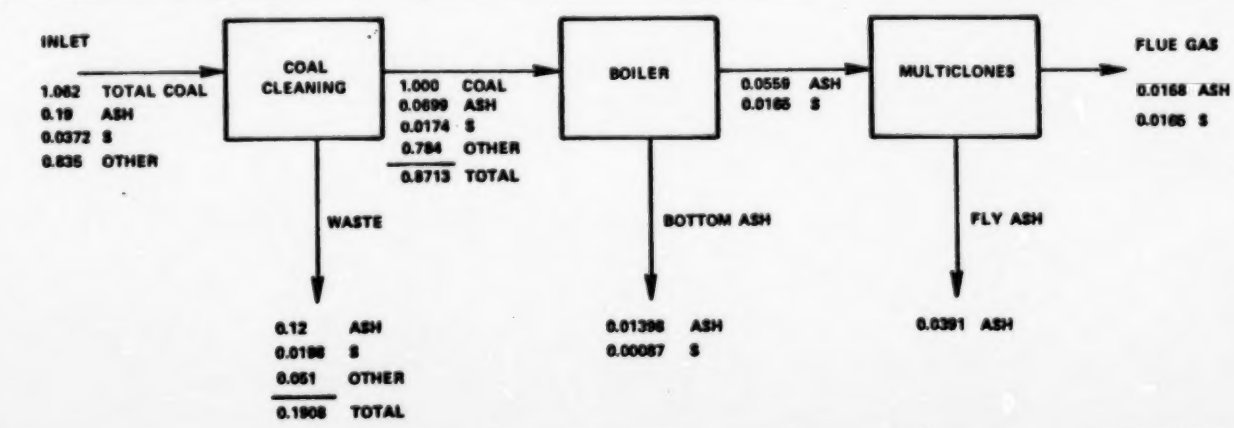
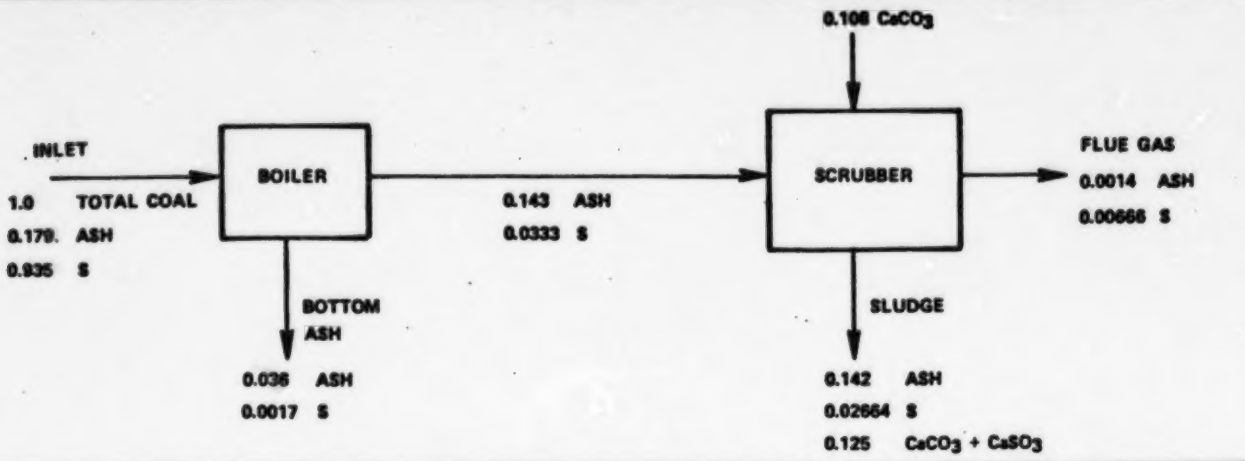
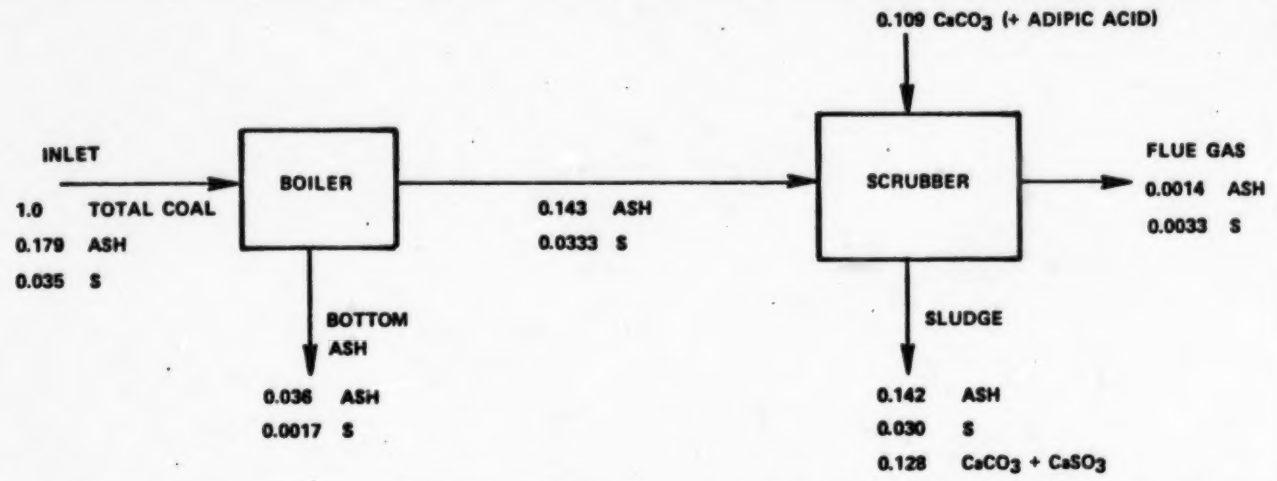


Figure 3. Material balance for coal cleaning.



▲ Figure 4. Material balance for limestone scrubbing.

▼ Figure 5. Material balance for limestone plus adipic acid scrubber.



both the concentration and the flow rate of the emissions. This is why the TWDS is so important when ambient conditions are not known.

If the concentration, dc_i, and the $DMEG_i$ are expressed in the units of grams of component per total grams of material, the WDS can also be expressed as:

$$WDS_i = DS_i \times mr = (dc_i/DMEG_i)mr$$

$$= mr_i/DMEG_i \quad (7)$$

If the DMEG were 1.0 g/g, the weighted discharge severity of that substance would be same as the flow rate of that substance. This means the WDS can be interpreted as the equivalent flow rate of a compound whose DMEG is 1.0 g/g.

Table 2 shows the results of the calculation of the Weighted Discharge Severity and Total Weighted Discharge Severity for the flue gas described above as the base case. Note the TWDS could also have been calculated by multiplying the Total Discharge Severity by the mass flow rate,

$$TWDS = TDS \times mr,$$

$$11.9 \times 10^9 = 5{,}260 \times 2.255 \times 10^6$$

To illustrate how the TWDS factor can be used to compare processes, let us look at a base case, a boiler using a 3.5% sulfur coal without any environmental controls, and compare the base case with four different methods for removing sulfur from the flue gas. These are 1. physical coal cleaning; 2. flue gas desulfurization using a limestone scrubber; 3. a limestone scrubber with the addition of adipic acid; and 4. a combination of physical coal cleaning and flue gas desulfurization with adipic acid addition. For this comparison, it will be assumed that regardless of treatment the particulate in the gas stream has the same composition as that given in Table 2. The Total Discharge Severity of the fly ash only is 4,670. The concentration of the particulate matter is 4,096,000 $\mu g/m^3$ ($\Sigma dc_{i\ \text{fly ash}}$). From this information the composite Discharge Multimedia Environmental Goal of the particulate can be calculated to be:

$$DMEG = \frac{\Sigma\ dc}{TDS} = \frac{4{,}096{,}000}{4{,}670} = 877\ \mu g/m^3$$

A composite DMEG has also been used for the waste ash from the coal cleaning process, the bottom ash, and the fly ash. It was assumed that all these materials have the same composition.

The basis for this comparison, the base case without any environmental controls, is a 500-MW power plant which uses 174,000 kg/h of coal. The coal contains 3.5% sulfur and 17.9% ash on a dry basis. This is the same coal used in a Tennessee Valley Authority study (*5,6*) on comparative costs. The plant has multiclones which remove 70% of the fly ash and 5% of the sulfur from the flue gas. The remaining 95% of the sulfur is assumed to leave as SO_2. Unit ratio material balances for the sulfur and ash are given in Figure 2. The unit ratio material balance used assumes that the same amount of CO, NO, CO_2, and hydrocarbons is formed in the boiler in each of the five cases given below (Figures 2, 3, 4, 5, and 6) and that scrubbing does not remove them.

The coal cleaning plant is assumed to be in the same Air Quality Control Region although not necessarily at the same site as the 500-MW boiler. Coal cleaning is assumed to reduce the sulfur to 2% and the ash to 8% of the resultant washed coal (*3*). Ninety-four percent of the initial heating value is recovered. Since the boiler must produce the same power output, this means 6.2% more coal must be used than when raw coal is charged to the boiler. The unit ratio material balances for sulfur and ash are given in Figure 3.

The limestone flue gas desulfurization (FGD) process was assumed to remove 80% of the sulfur entering the unit. This requires 1.3 mol of $CaCO_3$ per mol of sulfur removed (*6*). The scrubbing action and the multiclones remove 99% of the fly ash entering (*7*). When 1,500 ppm of adipic acid is added to the limestone slurry, the FGD system was assumed to remove 90% of the sulfur entering. This requires less limestone per unit of sulfur removal: 1.15 mol of $CaCO_3$ per mol of sulfur removed (*8*). No increase in particulate removal was assumed over the straight FGD process. The unit ratio balances for sulfur and ash are given in Figures 4 and 5.

When the coal cleaning process is used in combination with the limestone/adipic acid flue gas desulfurization, it is still assumed that 5% of the sulfur entering the boiler leaves with bottom ash and 90% of the sulfur entering the boiler is removed in the flue gas desulfurization unit. Similarly, 99% of the ash entering the boiler is removed in the multiclones and scrubbers. The unit ratio material balances for sulfur and ash are given in Figure 6.

Tables 3 through 7 give the concentrations, DMEGs, DSs, and WDSs for the components of each stream exiting from each of the five processes as well as the TWDS for each process. Table 8 summarizes the TWDS for the base case with no pollution controls, and the four cases with controls. The lowest ΣTWDS indicates the best job of reducing potential harmful emissions; thus, the lowest environmental loading per unit time results from the combination of all processes, Case 5, while physical coal cleaning does the poorest job of any of the cases having some control measures applied.

The method described here is essentially the Source Analysis Model developed at the EPA's Industrial Environmental Research Laboratory at Research Triangle Park, N.C. (*9*).

Cost effectiveness

The cost effectiveness of each of these processes can also be estimated using the concepts just presented. The "best" process may be defined as the one that produces the greatest reduction in TWDS for the least cost. Since the annual cost is in terms of cost per unit of production, the amount of pollution will be placed on the same basis for calculation purposes. Since our example is an electric utility, the hourly unit of production is a kWh/h of electricity. If it had been a chemical or metallurgical plant, the output would have been kg/h of product. If it had been a synthetic fuel plant, the output would have been J of available energy/h.

Table 9 summarizes a cost analysis based on human health DMEGs. To obtain the amount of pollution per unit of production in kg/kWh (Column 3), each TWDS in kg/h from Table 8 is divided by the hourly capacity of the plant, 500,000 kWh/h. Column 4 in Table 9 reports the decrease in the pollution unit of production compared to the Base Case with no environmental controls, while column 5 shows percent improvement over the Base Case. Column 6 shows the hourly cost (*8, 10, 11,* and *12*) of the abatement process, $/h, per hourly unit of production, kWh/h. Column 7 shows the pollution abatement cost per unit of pollution abatement; i.e., column 6 divided by column 4.

Column 8 shows the extra abatement cost per unit production (comparing a given treatment to the previous one in the table), divided by the improvement in the pollution abatement/unit production factor (again comparing a given treatment to the previous one in the table). Column 8 charges all the increased costs to the incremental decrease in pollution, instead of spreading it out over the whole pollution reduction as in column 7. For the case of limestone scrubbing compared to limestone scrubbing plus adipic acid, the differences in cost are so small that the incremental cost could easily be in error by a factor of five or more.

When adequate data are available, a parallel analysis must be made for TWDS for ecology. However, the parallel calculations were not done, since there was inadequate ecological data for the flue gas stream in the current example.

From the figures the physical coal cleaning has been shown to be the most cost-effective process; i.e., least abatement cost per unit of pollution abatement column 7, Table 9. The unit of pollution abatement can be viewed as 1 kg of a fictitious pollutant whose DMEG is 1 g/g (where all other compounds have been converted into this substance

Table 3. Base case: boiler without environmental controls.

Stream	dc_i Gas (μg/m³) Solid (μg/g)	DMEG$_i$ Air, Health (μg/m³) Solid, Health (μg/g)	DS_i	mr (kg/h)	WDS_i (kg/h)
Flue Gas				2.255E 06	
N_2	1.04E 09	NA	—		—
O_2	1.2 E 07	NA	—		—
CO_2	3.3 E 08	9.0 E 06	3.7 E 01		3.34 E 07
SO_2	6.3 E 06	1.3 E 04	4.85E 02		1.09 E 09
CO	4.0 E 04	4.0 E 04	1.00E 00		2.26 E 06
NO_2	6.4 E 05	9.0 E 03	7.11E 01		1.60 E 08
Organics	1.0 E 04	—			—
Ash	4.09E 06	8.77E 02	4.67E 03		1.053E 10
Bottom Ash	1.0 E 06	3.42E 03	2.92E 02	6.26 E 03	1.83 E 06
Fly Ash Removed	1.0 E 06	3.42E 03	2.92E 02	1.74 E 04	1.08 E 06

Σ TWDS = 1.19 E 10

Table 4. Case 2: boiler with physically cleaned coal.

Stream	dc_i Gas ($\mu g/m^3$) Solid ($\mu g/g$)	DMEG$_i$ Air, Health ($\mu g/m^3$) Solid, Health ($\mu g/g$)	DS$_i$	mr (kg/h)	WDS$_i$ (kg/h)
Flue Gas				2.246E 06	
N_2	1.04E 09	NA	—		—
O_2	1.2 E 07	NA	—		—
CO_2	3.30E 08	9.0 E 06	3.67E 01		8.24E 07
SO_2	3.1 E 06	1.3 E 04	2.38E 02		5.35E 08
CO	4.0 E 04	4.0 E 04	1.00E 00		2.24E 06
NO_2	6.4 E 05	9.0 E 03	7.11E 01		1.60E 08
Hydrocarbon	1.0 E 04	—	—		—
Ash	1.6 E 06	8.77E 02	1.83E 03		4.11E 09
Coal-Cleaning Waste Ash	1.0 E 06	3.42E 03	2.92E 02	2.09 E 04	6.10E 06
Bottom Ash	1.0 E 06	3.42E 03	2.92E 02	2.43 E 03	7.10E 05
Fly Ash Removed	1.0 E 06	3.42E 03	2.92E 02	6.83 E 03	1.99E 06
					Σ TWDS = 4.90E 09

Table 5. Case 3: boiler with FGD unit.

Stream	dc_i Gas ($\mu g/m^3$) Solid ($\mu g/g$)	DMEG$_i$ Air, Health ($\mu g/m^3$) Solid, Health ($\mu g/g$)	DS$_i$	mr (kg/h)	WDS$_i$ (kg/h)
Flue Gas				2.241E 06	
N_2	1.04E 09	NA	—		—
O_2	1.2 E 07	NA	—		—
CO_2	3.3 E 08	9.0 E 06	3.67E 01		8.22E 07
SO_2	1.3 E 06	1.3 E 04	1.00E 02		2.24E 08
CO	4.0 E 04	4.0 E 04	1.00E 00		2.24E 06
NO_2	6.4 E 05	9.0 E 03	7.11E 01		1.59E 08
Hydrocarbon	1.0 E 04	—	—		—
Ash	1.33E 05	8.77E 02	1.52E 02		3.41E 08
Bottom Ash	1.0 E 06	3.42E 03	2.92E 02	6.26 E 03	1.83E 06
Sludge				4.65 E 04	
Ash	5.3 E 05	3.43E 03	1.55E 02		7.21E 06
$CaCO_3 + CaSO_3$ (As, Ca^{++})	1.62E 05	4.8 E 04	3.38E 00		1.57E 05
					Σ TWDS = 8.18E 08

Table 6. Case 4: boiler with FGD unit (adipic acid added)

Stream	dc_i Gas ($\mu g/m^3$) Solid ($\mu g/g$)	DMEG$_i$ Air, Health ($\mu g/m^3$) Solid, Health ($\mu g/g$)	DS$_i$	mr (kg/h)	WDS$_i$ (kg/h)
Flue Gas				2.241E 06	
N_2	1.04E 09	NA	—		—
O_2	1.2 E 07	NA	—		—
CO_2	3.3 E 08	9.0 E 06	3.67E 01		8.22E 07
SO_2	6.3 E 05	1.3 E 04	4.85E 01		1.09E 08
CO	4.0 E 04	4.0 E 04	1.00E 00		2.24E 06
NO_2	6.4 E 05	9.0 E 03	7.11E 01		1.59E 08
Hydrocarbon	1.0 E 04	—	—		—
Ash	1.33E 05	8.77E 02	1.52E 02		3.41E 08
Bottom Ash	1.0 E 06	3.42E 03	2.92E 02	6.26 E 03	1.83E 06
Sludge				4.65 E 04	
Ash	5.3 E 05	3.43E 03	1.55E 02		7.21E 06
$CaCO_3 + CaSO_3$ (As, Ca^{++})	1.60E 05	4.8 E 04	3.33E 01		1.55E 05
					Σ TWDS = 7.03E 08

Table 7. Case 5: boiler with physically cleaned coal and FGD unit (adipic acid added).

Stream	dc_i Gas (μg/m³) Solid (μg/g)	DMEG$_i$ Air, Health (μg/m³) Solid, Health (μg/g)	DS$_i$	mr (kg/h)	WDS$_i$ (kg/h)
Flue Gas				2.239E 06	
N_2	1.04E 09	NA	—		—
O_2	1.2 E 07	NA	—		—
CO_2	3.3 E 08	9.0 E 06	3.67E 01		8.22E 07
SO_2	3.1 E 05	1.3 E 04	2.38E 01		5.33E 07
CO	4.0 E 04	4.0 E 04	1.00E 00		2.24E 06
NO_2	6.4 E 05	9.0 E 03	7.11E 01		1.59E 08
Hydrocarbon	1.0 E 04	—	—		—
Ash	6.2 E 04	8.77E 02	7.08E 01		1.59E 08
Coal Cleaning					
Waste Ash	1.0 E 06	3.42E 03	2.92E 02	2.09 E 04	6.10E 06
Bottom Ash	1.0 E 06	3.42E 03	2.92E 02	2.43 E 04	7.10E 05
Sludge				2.06 E 04	
Ash	4.7 E 05	3.42E 03	1.37E 02		2.83E 06
$CaCO_3 + CaSO_3$ (As, Ca^{++})	1.80E 05	4.8 E 04	3.75E 00		7.73E 04

Σ TWDS = 4.65E 08

through the use of the weighting factor, DMEG$_i$). Coal cleaning alone, however, only reduces the potential harm, TWDS, by 59%, see column 5, Table 9. Any of the other processes are seen to reduce the pollution, TWDS, by over 93%.

The increase in the incremental cost of electricity using the combined process will only be about 50% greater than for physical coal cleaning. However, as can be seen, the incremental cost of reducing the amount of pollution per unit of production from 1,406 to 930 kg/kWh will be ($2.94/kg) × 10^{-6}. This is about 15 times the comparable incremental cost for physical coal cleaning alone, ($0.18/kg) × 10^{-6}. Note that as the percent pollutant removal increases, the incremental cost to remove a unit of pollutant also increases. Such a result, of course, is not unexpected.

This analysis provides industry, environmentalists, and governmental regulators with a comparison of alternatives which can be used to determine what level of control is most desirable.

Caution is again advised in placing too much reliance in the absolute magnitude of the numbers generated in this type of analysis. Since the uncertainty of the DMEGs is unknown and the errors associated with any given DMEG may be large, the analysis should be viewed as indicative of trends rather than as absolute bases for decisions. The methodology for the analysis is conceptually sound, but the interpretation of the results requires engineering judgement, as usual.

Gasification of coal

The following example illustrates some additional uses of the DMEGs in a study (*12*) involving a Chapman gasifier converting coal to low-energy gas. The example which follows is less comprehensive than the flue gas desulfurization example and does not include an economic analysis. Rather, the intention of the coal gasification study was to determine which streams, including fugitive emission discharges, were potentially hazardous to human health. The study not only identifies the potentially hazardous streams, but also identifies which components in the stream contribute to the possible toxic nature of the stream. This information is useful not only in devising a control strategy for the emission, but in setting the relative toxicity of the streams. The measure of the relative toxicity of the streams used in this example is the Total Discharge Severity. In this example, the magnitude of the insult to the environment is not being considered; therefore, it is not necessary to calculate the Total Weighted Discharge Severity.

Figure 7 shows a simplified process flow diagram for the Chapman facility showing waste and process streams and sampling points. For purposes of discussion, the unit may be subdivided into coal-handling, gasification, and gas-purification sections. Coal handling includes delivery and storage of presized bituminous coal, conveying, and holding this coal in a hopper located over the gasifier.

Gasification consists of producing raw, low-energy gas from coal using fixed-bed, atmospheric-pressure, single-staged Chapman gasifiers. Coal is fed to the gasifier by a rotating barrel valve and is spread across the top of the bed by a distribution arm. A steam/air mixture is continuously fed to the gasifier to produce a low-energy fuel gas at 850 to 950 K. The coal is fed and ash is removed from the gasifier intermittently. Ash is removed from a water-sealed ash pan by a plow. During the operation of the gasifier, when agglomerates form in the gasifier, pokeholes in the top of the gasifier are opened briefly and rods are inserted manually to break up the agglomerates.

Gas purification begins with removal in a cyclone separator of some of the particulate matter in the hot gas leaving

Table 8. Comparison of environmental loadings.

No.	Case, Treatment	Σ TWDS × 10^{-6} (kg/h)
1.	Base case, no environmental controls	11,900
2.	Physical coal cleaning	4,900
3.	Limestone flue gas desulfurization (FGD)	818
4.	Limestone flue gas desulfurization + adipic acid	703
5.	Limestone FGD + adipic acid, physically cleaned coal	465

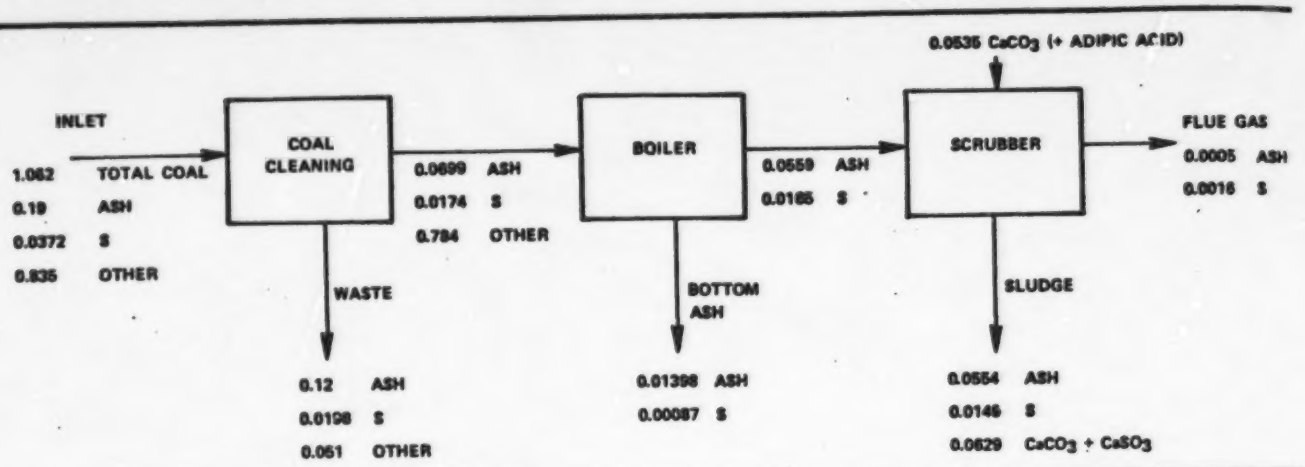


Figure 6. Material balance for coal cleaning plus limestone plus adipic acid scrubber.

the gasifier. Devolatilized coal particles, tar, and ash account for most of the particulate matter collected. Hot gas from the cyclone is cooled to 320 K using in-line quench water sprays followed by tray scrubbers and a spray scrubber as indicated in Figure 7. Tar, condensible oils, and most of the remaining particulates are removed from the gas streams. Gas leaving the spray scrubber is called clean product gas and is put directly to the process furnaces as fuel.

Flow rates of the primary process streams are given in Table 10 to indicate the size of the gasifier installation.

Table 11 shows the Total Discharge Severities for selected stream. All these streams have TDS values, which would indicate a significant potential hazard to human health, should direct exposure to those streams be possible. The TDS values for the separator vent gas, gasifier ash, and cyclone dust indicate a lower potential hazard than the separator liquor. The results indicate top priority should be given to treatment or containment of the byproduct tar/oil and the coal feeder vent gas streams. The plant tested currently adds the coal feeder vent gases to the product gas stream (*14*).

Table 12 shows the analysis and Discharge Severities for the separator liquor, essentially an aqueous stream. As can be seen, the DS values for the phenols, ammonia, and cyanide are high. Since the separator liquor stream is not an effluent stream, treatment is not necessary. Leaks from the system or any liquor blowdown or bleed need to be considered highly toxic. Any handling of the liquor during repairs or shutdowns should be done with care to avoid direct or extended exposure.

Fifteen consent decree pollutants were identified in the separator liquor, and 11 components or classes of compounds listed in Table 12 show DS values greater than unity.

The analyses conducted on the gasification example indicate not only which streams are potentially hazardous, but also what compounds or classes of compounds within the streams may be potential hazards to human health or to the ecology. A knowledge of the hazardous compounds or classes of compounds present better enables us to design a cost-optimal control scheme. #

Nomenclature

ac	– Concentration of a component in the ambient medium, air, water, or land
ACGIH	– American Conference of Governmental Industrial Hygienists
AMEG	– Ambient Multimedia Environmental Goal,

Table 9. Cost analysis based on human health DMEGs.

(1) Case No.	(2) Case, Treatment	(3) Pollution/ Unit Production (kg/kWh)	(4) Pollution* Abatement/ Unit Production (kg/kWh)	(5) % Improvement	(6) Abatement* Cost/Unit Production ($/kWh)	(7)=(6)/(4) Abatement* Cost/ (Pollution Abatement) ($/kg) × 10^6	(8) Δ (Abatement Cost)** Δ (Pollution Abatement) ($/kg) × 10^6
1	Base case, no environmental controls	23,800	—	—	—	—	—
2	Physical coal cleaning	9,800	14,000	59.0	0.0025	0.179	0.179
3	Limestone FGD	1,636	22,164	93.1	0.0046	0.208	0.257
4	Limestone + adipic acid	1,406	22,394	94.1	0.0047	0.210	0.435
5	Coal cleaning + limestone + adipic acid	930	22,870	96.1	0.0061	0.267	2.94

*Compared to base case: (5) to (1), (4) to (1), etc. **Compared to previous case: (5) to (4), (4) to (3), etc.

concentration units

ANSI – American National Standards Institute

AS – Ambient Severity of a component, defined by Eq. 3, dimensionless

CIIT – Chemical Industry Institute of Toxicology

dc – Concentration of a component in a discharge stream

DIPPR – Design Institute for Physical Property Data, AIChE

DMEG – Discharge Multimedia Environmental Goal, concentration units

DS – Discharge Severity, dimensionless, defined by Eq. 1

ECAO – Environmental Criteria and Assessment Office (EPA, RTP)

EPA – U.S. Environmental Protection Agency

FDA – Federal Drug Administration

ID – Identification number or symbol

IERL – Industrial Environmental Research Laboratory

IRLG – Interagency Regulatory Liaison Group

LD_{50} – Lowest Dose causing death in 50% of the tested population

MEG(s) – Multimedia Environmental Goal(s)

MEGDAT – Computerized EPA data base for Environmental Assessment, MEGs, etc.

mr – Mass flow rate of a discharge stream, mass/unit time

NAE – National Academy of Engineering

NAS – National Academy of Science

NIOSH – National Institute for Occupational Safety and Health

OSHA – Occupational Safety and Health Administration

RTP – Research Triangle Park, North Carolina

TAS – Total Ambient Severity, defined for health or ecology by Eq. 4

TDS – Total Discharge Severity, defined by Eq. 2

TLVs – Threshold Limit Values recommended by the ACGIH

TWDS – Total Weighted Discharge Severity, defined by Eq. 6

WDS – Weighted Discharge Severity, defined by Eq. 5

Subscript

i – Component *i*

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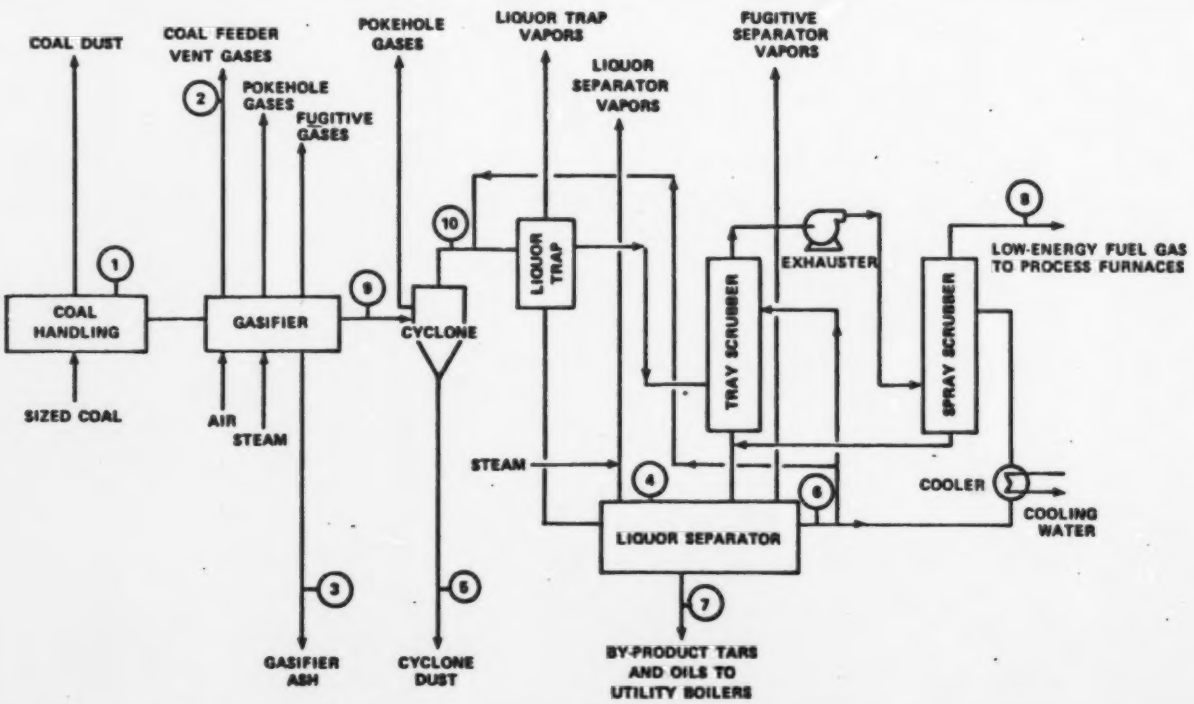

Figure 7. Simplified flow diagram for Chapman facility.

Table 10. Mass balance.

Stream Description	Flow Rate, kg/s
Input Streams	
Air	0.77
Steam	0.16
Coal Feed	0.304
Total	1.234
Output Streams	
Gasifier Ash	0.0185
Cyclone Dust	0.00161
Cooled Product Gas	0.989
Byproduct Tar	0.0304
Coal Feeder Vent gas	0.00611
Liquor Separator Vapors	0.0539
Total	1.100
Input Minus Output	0.134 kg/s
% of Input Unaccounted for	10.9

Table 11. Total discharge severities for streams.

Sample Point	Stream	TDS
2	Coal Feeder Vent Gas	250,000
3	Gasifier Ash	5,420
4	Separator Vent Gas	1,540
5	Cyclone Dust	2,040
6	Separator Liquor	229,000
7	Byproduct Tar/Oil	1,980,000

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Table 12. Separator ...

MEG ID No.	Compound(s)	Stream Concentration (μg/L)	DMEG Water, Health (μg/L)	DS
01A220	>C_6 Alkanes, (C_9)	1.0E 05	1.6E 07	6.0E-03
01AN23	Methylcyclohexane	4.0E 02	NA	—
050000	>C_6 Alkylalcohols	1.2E 04	NA	—
050000	>C_{15} Alkylalcohols	5.4E 03	NA	—
03AN08	Anisoles	1.3E 06	NA	—
08A200	Phthalic acid	4.0E 03	3.1E 06	1.3E-03
08D280	*Phthalates	2.2E 04	7.5E 04	2.9E-01
08D200	Adipates (Diethyl)	1.9E 04	1.1E 06	1.7E-02
10C020	Aniline	3.0E 03	2.9E 05	1.0E-02
10C040	Aminotoluene	3.8E 03	1.7E 03	2.2E 00
10C060	Dimethylanilines	1.0E 03	3.8E 05	2.6E-03
23C02N	Methylpyrroline	1.3E 03	NA	—
18A020	*Phenol	7.2E 05	5.0E 00	1.4E 05
18A080	*C_2 Alkylphenols	3.7E 05	5.0E 00	7.4E 04
18A160	*C_3 Alkylphenols	5.0E 04	5.0E 00	1.0E 04
21A020	Naphthalene	1.7E 04	7.5E 05	2.3E-02
21A040	Methylnaphthalene	5.1E 03	3.4E 06	1.5E-03
21A120	*Acenaphthalene	4.1E 03	NA	—
21D080	*Benzoperylene	3.0E 04	NA	—
23A040	Methylpyridine	3.0E 03	5.3E 05	5.7E-01
23A140	C_2-Alkylpyridine	3.8E 03	2.7E 05	1.4E-03
23A120	C_3-Alkylpyridine	1.0E 03	1.0E 06	1.0E-03
23C040	Indole	5.3E 04	1.7E 05	3.1E-01
23C060	Methylindole	8.9E 03	6.8E 05	1.3E-02
23B020	Quinoline	3.1E 03	2.4E 05	1.3E-02
23B040	Methylquinoline	1.8E 03	8.3E 05	2.2E-03
23B04N	C_3 Alkylquinoline	2.4E 03	NA	—
270000	Lithium	3.0E 00	3.3E 02	9.0E-03
290000	Potassium	2.0E 04	NA	—
300000	Rubidium	1.0E 01	1.0E 06	5.6E-06
310000	Cesium	1.0E 00	1.2E 06	8.3E-07
330000	Magnesium	2.0E 03	9.4E 04	2.1E-02
340000	Calcium	2.0E 04	2.4E 05	8.3E-02

(NTIS PB80-133168) (July, 1979).
10. Personal communication from V. W. Uhl, University of Virginia, Charlottesville, VA (Nov., 1979).
11. Buroff, J., B. Hylton, S. Keith, S. Strauss, and L. McCandless, "Technology Assessment Report for Industrial Boiler Applications: Coal-Cleaning and Low Sulfur Coal," Versar, Inc., Springfield, VA, EPA-600/7-79-178c (Dec., 1979).
12. Page, G. C., W. J. Rhodes, and T. K. Janes, "Environmental Assessment Results and Control Technology Needs for Low-Btu Gasification Facilities," *AIChE 72nd Nat. Meeting*, San Francisco, CA (Nov., 1979).
13. Personal communication from G. C. Page (Feb., 1980).

Appendix A. Categorizing MEGs for organic chemicals.

Category 01: Aliphatic Hydrocarbons
- Alkanes and Cyclic Alkanes
- Alkenes, Cyclic Alkenes, and Dienes
- Alkynes

Category 02: Alkyl Halides
- Saturated Alkyl Halides
- Unsaturated Alkyl Halides

Category 03: Ethers
- Noncyclic Aliphatic or Aromatic Ethers
- Cyclic Ethers

Category 04: Halogenated Ethers
- Monohalogenated Ethers
- Dihalogenated and Polyhalogenated Ethers

Category 05: Alcohols
- Primary Alcohols
- Secondary Alcohols
- Tertiary Alcohols

Category 06: Glycols, Epoxides
- Glycols
- Epoxides

Category 07: Aldehydes, Ketones
- Aldehydes
- Ketones
- Aldehydes and Ketones with Additional Functional Groups

Category 08: Carboxylic Acids and Derivatives
- Carboxylic Acids

... liquor.

MEG ID No.	Compound(s)	Stream Concentration (μg/L)	DMEG Water, Health (μg/L)	DS
350000	Strontium	8.0E 01	4.6E 04	1.7E-03
360000	Barium	3.0E 02	5.0E 03	6.0E-02
370000	Boron	9.0E 03	4.7E 04	1.9E-01
42A300	Carbonate	2.0E 06	NA	—
430000	Silicon	2.0E 03	1.5E 05	1.3E-02
450000	Tin	3.0E 01	NA	—
47B100	*Ammonia	5.0E 06	2.5E 03	2.0E 03
47A360	*Cyanide	1.0E 06	5.0E 02	2.0E 03
480000	Phosphorus	2.0E 04	1.5E 04	1.3E 00
490000	*Arsenic	8.0E 02	2.5E 02	3.2E 00
500000	*Antimony	7.0E 01	7.5E 03	9.3E-03
47A380	Thiocyanate	7.0E 01	NA	—
53A200	Sulfide	<1.0E 04	NA	—
53A300	Sulfate	1.0E 06	NA	—
540000	*Selenium	2.0E 03	5.0E 01	4.0E 01
560000	Fluorine	2.0E 05	3.8E 04	5.3E 00
570000	Chloride	3.0E 06	1.3E 06	2.3E 00
580000	Bromine	3.0E 02	NA	—
590000	Iodine	3.0E 02	NA	—
600000	Scandium	2.0E 00	8.0E 05	2.5E-06
610000	Yttrium	5.0E 00	1.5E 04	3.3E-04
620000	Titanium	1.0E 02	9.0E 04	1.1E-03
630000	Zirconium	1.0E 01	7.5E 04	1.3E-04
660000	Niobium	8.0E 00	3.3E 05	2.4E-05
700000	Tungsten	1.0E 01	1.5E 04	6.7E-04
720000	Iron	1.0E 03	1.5E 03	6.7E-01
780000	*Copper	1.0E 01	5.0E 03	2.0E-03
790000	*Silver	2.0E 00	2.5E 02	8.0E-03
820000	*Cadmium	5.0E 00	5.0E 01	1.0E-01
830000	*Mercury	3.0E-04	1.0E 01	3.0E-05
840000	Lanthanum	7.0E 00	1.7E 06	4.1E-06
850000	Cerium	3.0E 00	5.5E 05	5.5E-06
				TDS = 2.29E 05

NA: *DMEG* value not available. *Consent decree pollutants.

Appendix A. (Continued)

Carboxylic Acids with Additional Functional Groups
Amides
Esters

Category 09: Nitriles
Aliphatic Nitriles
Aromatic Nitriles

Category 10: Amines
Primary Aliphatic Amines and Diamines
Secondary Aliphatic Amines
Aromatic Amines and Diamines
Tertiary Amines (Alkyl, Aryl)

Category 11: Azo Compounds; Hydrazine Derivatives
Azo Compounds
Hydrazine Derivatives

Category 12: Nitrosamines
Aliphatic Nitrosamines
Aromatic Nitrosamines

Category 13: Thiols, Sulfides and Disulfides
Thiols
Sulfides, Disulfides

Category 14: Sulfonic Acids, Sulfoxides
Sulfonic Acids
Sulfoxides

Category 15: Benzene, Substituted Benzene Hydrocarbons
Benzene and Monosubstituted Benzene Hydrocarbons
Disubstituted and Polysubstituted Benzene Hydrocarbons

Category 16: Halogenated Aromatic Compounds
Ring Substituted Aromatics
Aromatics with Halogenated Alkyl Side Chain

Category 17: Aromatic Nitro Compounds
Simple Aromatic Nitro Compounds
Aromatic Nitro Compounds With Other Functional Groups

Category 18: Phenols
Monohydrics
Dihydrics, Polyhydrics
Fused Ring Hydroxy Compounds

Category 19: Halogenated Phenolic Compounds
Halophenols
Halogenated Cresols

Category 20: Nitrophenolic Compounds
Nitrophenols
Nitrocresols

Category 21: Fused Polycyclic Hydrocarbons
Two- and Three-Ring Fused Polycyclic Hydrocarbons
Four-Ring Fused Polycyclic Hydrocarbons
Five-Ring Fused Polycyclic Hydrocarbons
Compounds with More than Five Fused Rings

Category 22: Fused Nonalternant Polycyclic Hydrocarbons
Two- and Three-Ring Fused Nonalternant Polycyclic Hydrocarbons
Four-Ring Fused Nonalternant Polycyclic Hydrocarbons
Five-Ring Fused Nonalternant Polyclic Hydrocarbons
Compounds with More Than Five Fused Rings

Category 23: Heterocyclic Nitrogen Compounds
Pyridine and Substituted Pyridines
Fused Six-Membered Ring Heterocycles
Pyrrole and Fused Ring Derivatives of Pyrrole
Nitrogen Heterocycles Containing Additional Hetero-atoms

Category 24: Heterocyclic Oxygen Compounds
One- and Two-Ring Heterocyclic Oxygen Compounds
Three- or More-Ring Heterocyclic Oxygen Compounds

Category 25: Heterocyclic Sulfur Compounds
One-Ring Heterocyclic Sulfur Compounds
Two- or More-Ring Heterocyclic Sulfur Compounds

Category 26: Organophosphorous Compounds
Aliphatic Organophosphorous Compounds
Aromatic Organophosphorous Compounds

Appendix B. Coding system for MEG values.

Codes following the acronym AMEG or DMEG indicate: (1) the medium addressed, (2) the type of effect, (3) the data type serving as the basis for the specific model, and (4) the particular equation that results in the quantitative *MEG*. The meaning of each character of the code (left to right) is indicated below:

Code	Description
1 ...	Medium: A, air W, water L, land or solid waste
2 ...	Type of effect: H, human health E, ecology C, carcinogenic effect T, teratogenic effect
3 ...	Data basis for the model, one of the following numbers: 1. TLV, NIOSH recommendation, or subjective opinion of an agency. 2. Laboratory data, largely lethal studies; e.g., threshold limit median (TLm) describes the lethal concentration of a pollutant to 50% of a tested aquatic species population; LD_{50} values describe a toxicant dose, mg/kg of animal body weight, lethal to 50% of the population tested. Oral rat (lethal dose) data are preferred. 3. MEG value for one medium calculated from MEG value from another medium; e.g., AMEG for land calculated from AMEG for water. 4. A U.S. federal regulation or criterion.
4 ...	Equation designation used to calculate MEG.
5 ...	Either designates a dimension (e.g., $\mu g/m^3$, ppm, $\mu g/g$) or distinguishes between marine water or freshwater MEG.

Appendix C-1. Equations to generate AMEGs.

Basis, B	Equation
Medium: Air (μg/m³)	
TLV®* (mg/m³)	AMEG(AH 1.1) = 2.38 × B
NIOSH recommendation* (mg/m³)	AMEG(AH 1.2) = 2.38 × B
OSHA regulation* (mg/m³)	AMEG(AH 1.3) = 2.38 × B
Lethal dose (mg/kg)	AMEG(AH 2.1) = 0.081 × B
NAAQS, primary (μg/m³)	AMEG(AH 4.1) = B
TLV† (mg/m³)	AMEG(AC 1.1) = 2.38 × B
NIOSH recommendation† (mg/m³)	AMEG(AC 1.2) = 2.38 × B
OSHA regulation† (mg/m³)	AMEG(AC 1.3) = 2.38 × B
Lowest dose (mg/kg) to produce oncogenic response	AMEG(AC 2.1) = C_1§ × B
Lowest dose (mg/kg) to produce teratogenic response	AMEG(AT 2.1) = C_1§ × B
AMEG(AT 2.1) = 1.66 × 1/B	
Lowest effective 24-h concentration for plants (μg/m³)	AMEG(AE 2.1) = 0.1 × B
NAAQS, secondary (μg/m³)	AMEG(AE 4.1) = B
Medium: Water (μg/L)	
TLV* (mg/m³)	AMEG(WH 1.1) = 13.8 × B
NIOSH recommendation* (mg/m³)	AMEG(WH 1.2) = 13.8 × B
OSHA regulation* (mg/m³)	AMEG(WH 1.3) = 13.8 × B
Lethal dose (mg/kg)	AMEG(WH 2.1) = 0.4 × B
Preferred AMEG(AH) (μg/m³)	AMEG(WH 3.1) = 15 × B
Lowest drinking water standard or criterion (μg/L)	AMEG(WH 4.1) = B
Lowest AMEG(AC) (μg/m³)	AMEG(WC 3.1) = 15 × B
Level associated with cancer risk of 10^{-5} in proposed water quality criteria (μg/L)	AMEG(WC 4.1) = B
AMEG(AT 2.1) (μg/m³)	AMEG(WT 3.1) = 15 × B
Hazard level (specified) (μg/L)	AMEG(WE 1.1) = 0.2 × B
Application factor§ and threshold limit median, *TLm*§ (μg/L)	AMEG(WE 1.2) = TLm × B
Concentration factor§ and allowable concentration in fish§ (μg/kg)	AMEG(WE 1.3) = allow. conc. / conc. factor
Threshold limit median, TLm for most sensitive species (μg/L)	AMEG(WE 2.1) = 0.05 × B
Tainting level (μg/L)	AMEG(WE 2.2) = B
Lowest water quality criterion, marine (μg/L)	AMEG(WE 4.1.1) = B
Lowest water quality criterion, freshwater (μg/L)	AMEG(WE 4.1.2) = B
Lowest water quality criterion, irrigation (μg/L)	AMEG(WE 4.2) = B
Medium: Soil (μg/g)	
Preferred AMEG(WH) (μg/L)	AMEG(LH 3.1) = 0.2 × B
Lowest AMEG(WC) (μg/L)	AMEG(LC 3.1) = 0.2 × B
AMEG(WT 3.1) (μg/L)	AMEG(LT 3.1) = 0.2 × B
Lowest AMEG(WE) (μg/L)	AMEG(LE 3.1) = 0.2 × B

*For compounds not indicated to be carcinogens.
†For compounds known or suspected to be carcinogens.
§C_1 ranges from 0.02 to 0.08 depending on extent of positive test data.

Appendix C-2. Equations to generate DMEGs.

Basis, B	Equation
Medium: Air μg/m³	
TLV®* (mg/m³)	DMEG(AH 1.1) = 1,000 × B
NIOSH Recommendation* (mg/m³)	DMEG(AH 1.2) = 1,000 × B
OSHA Regulation* (mg/m³)	DMEG(AH 1.3) = 1,000 × B
Lethal dose (mg/kg)	DMEG(AH 2.1) = 45 × B
Lowest effective or lethal concentration (μg/m³)	DMEG(AH 2.2) = 0.1 × B
TLV† (mg/m³)	DMEG(AC 1.1) = 1,000 × B
NIOSH Recommendation† (mg/m³)	DMEG(AC 1.2) = 1,000 × B
OSHA Regulation† (mg/m³)	DMEG(AC 1.3) = 1,000 × B
Lowest dose (mg/kg) to produce oncogenic response	DMEG(AC 2.1) = c_2§ × 1/B
Lowest dose (mg/kg) to produce teratogenic response	DMEG(AT 2.1) = C_2§ × 1/B
Lowest effective 24-hr concentration for plants (μg/m³)	DMEG(AE 2.1) = B
Medium: Water (μg/L)	
Preferred DMEG(AH) (μg/m³)	DMEG(WH 3.1) = 15 × B
Lowest drinking water standard or criterion (μg/L)	DMEG(WH 4.1) = 5 × B
Lowest DMEG(AC) (μg/m³)	DMEG(WC 3.1) = 15 × B
Level associated with cancer risk of 10^{-4} in proposed water quality criterion (μg/L)	DMEG(WC 4.1) = B
DMEG(AT 2.1) (μg/m³)	DMEG(WT 3.1) = 15 × B
Threshold limit median for most sensitive species (μg/L)	DMEG(WE 2.1) = 0.1 × B
Lowest water quality criterion, marine (μg/L)	DMEG(WE 4.1) = 5 × B
Lowest water quality criterion, freshwater (μg/L)	DMEG(WE 4.1.2) = 5 × B
Lowest water quality criterion, irrigation (μg/L)	DMEG(WE 4.2) = 5 × B
Medium: Land (μg/g)	
Lowest DMEG(WH) (μg/L)	DMEG(LH 3.1) = 0.2 × B
Lowest DMEG(WC) (μg/L)	DMEG(LC 3.1) = 0.2 × B
DMEG(WT 3.1) (μg/L)	DMEG(LT 3.1) = 0.2 × B
Lowest DMEG(WE) (μg/L)	DMEG(LE 3.1) = 0.2 × B

*For compounds not indicated to be carcinogens.
†For compounds known or suspected to be carcinogens.
§C_2 ranged from 8.8 to 33.3 depending on extent of positive test data.

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